Simulated White Light Imaging from a Data-driven, Time-dependent Magnetohydrodynamic Model of the Corona and Heliosphere

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Predictive Science Inc.

MAS

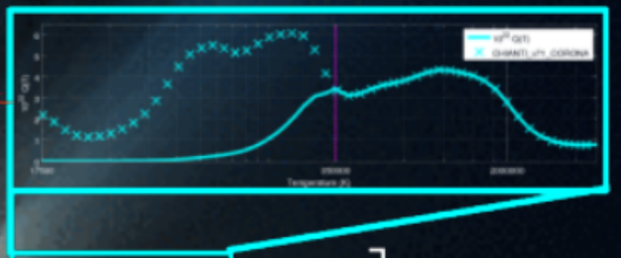
MAGNETOHYDRODYNAMIC ALGORITHM OUTSIDE A SPHERE

$$\frac{\partial \mathbf{A}}{\partial t} = \mathbf{v} \times (\nabla \times \mathbf{A}) - \boxed{\frac{c^2\,\eta}{4\,\pi} \nabla \times \nabla \times \mathbf{A}}$$

RESISTIVITY

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho\,\mathbf{v})$$

$$\frac{\partial T}{\partial t} = -\nabla \cdot (T\mathbf{v}) - (\gamma - 2)\,(T\,\nabla \cdot \mathbf{v}) + \frac{\gamma - 1}{2\,k}\frac{m_p}{\rho}\left[\boxed{-\nabla \cdot (\mathbf{q}_1 + \mathbf{q}_2)} - \boxed{\frac{\rho^2}{m_p^2} Q(T)} + \boxed{H}\right]$$



RADIATIVE COOLING

THERMAL CONDUCTION

$$\mathbf{q}_1 = -f(r)\,\beta_{T_{\rm cut}}(T)\,\kappa_0\,T^{5/2}\,\hat{\mathbf{b}}\hat{\mathbf{b}} \cdot \nabla T$$

$$\mathbf{q}_2 = (1 - f(r))\,\frac{k}{(\gamma - 1)}\frac{\rho}{m_p} T\,\mathbf{v}\,\hat{\mathbf{b}}\hat{\mathbf{b}}$$

CORONAL HEATING

$$H = H^* + \frac{\rho}{4\,\lambda_\perp}\left[|z_-|\,z_+^2 + |z_+|\,z_-^2\right]$$

$$\lambda_\perp = \boxed{\lambda_0}\sqrt{\frac{B_w}{|\mathbf{B}|}} \quad |z_\pm(r = R_\odot)| = \boxed{z_0}$$

ALFVÉN WAVES

$$\boxed{\frac{\partial \epsilon_\pm}{\partial t} = -\nabla \cdot (\epsilon_\pm\,[\mathbf{v} \pm \mathbf{v}_\mathbf{A}]) - \frac{\epsilon_\pm}{2}\nabla \cdot \mathbf{v}}$$

$$\frac{\partial \mathbf{v}}{\partial t} = -\mathbf{v} \cdot \nabla\,\mathbf{v} + \frac{1}{\rho}\left[\frac{1}{c}\mathbf{J} \times \mathbf{B} - \nabla p - \boxed{\nabla\left(\frac{\epsilon_+ + \epsilon_-}{2}\right)} + \rho\,\mathbf{g}\right] + \boxed{\frac{1}{\rho}\nabla \cdot (\nu\rho\nabla\,\mathbf{v})} + \boxed{\frac{1}{\rho}\nabla \cdot \left(S\,\rho\,\nabla\frac{\partial \mathbf{v}}{\partial t}\right)}$$

VISCOSITY

SEMI-IMPLICIT OPERATOR

WAVE TURBULENCE

$$\boxed{\begin{aligned}\frac{\partial z_\pm}{\partial t} = &-(\mathbf{v} \pm \mathbf{v}_\mathbf{A}) \cdot \nabla\,z_\pm - \frac{z_\pm\,|z_\mp|}{2\,\lambda_\perp} \\ &+ \frac{z_\pm}{4}(\mathbf{v} \mp \mathbf{v}_\mathbf{A}) \cdot \nabla\,(\ln \rho) + \frac{z_\mp}{2}(\mathbf{v} \mp \mathbf{v}_\mathbf{A}) \cdot \nabla\,(\ln |\mathbf{v}_\mathbf{A}|)\end{aligned}}$$

$\nabla \cdot \mathbf{B} = 0$ $\quad \mathbf{B} = \nabla \times \mathbf{A}$ $\quad \mathbf{J} = \frac{c}{4\,\pi}\nabla \times \mathbf{B}$ $\quad p = 2\,k\,T\,\rho/m_p$ $\quad \mathbf{g} = -g_0\,R_\odot^2\,\hat{\mathbf{r}}/r^2$ $\quad \gamma = 5/3$ $\quad \hat{\mathbf{b}} = \mathbf{B}/|\mathbf{B}|$ $\quad \mathbf{v}_\mathbf{A} = \mathbf{B}/\sqrt{4\,\pi\,\rho}$ $\quad B_w = 6.09\,G$ $\quad v_c^2 = \gamma\,p/\rho$

$$B_{T_{\rm cut}}(T) = \begin{cases} (T/T_{\rm cut})^{-5/2} & T < T_{\rm cut} \\ 1, & T \geq T_{\rm cut} \end{cases} \qquad T_{\rm cut} = 3.5 \times 10^5\,K \qquad f(r) = 1 - 0.5\tanh\left[(r - 10\,R_\odot)/R_\odot\right]$$

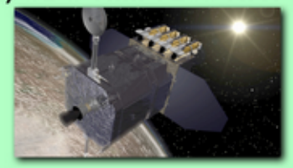
$$S = (\Delta t^2\,\tilde{k}^2) \div (C_w^2/(1 - C_f)^2 - 1) \qquad C_f = \Delta t\,\tilde{k} \cdot \mathbf{v} \qquad C_w^2 = 0.25\,\Delta t^2\,\tilde{k}^2\,(v_c^2 + |\mathbf{v}_\mathbf{A}|^2) \qquad \tilde{k}^2 = 4\,(\Delta r^{-2} + (r\,\Delta\theta)^{-2} + (r\,\Delta\phi\,\sin\theta)^{-2})$$

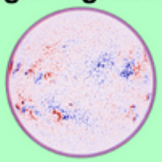
predsci.com/mas

The PSI 2024 Eclipse Prediction Real-Time Pipeline

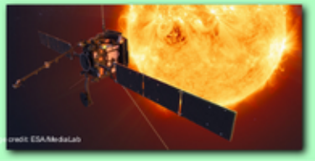
Data Acquisition

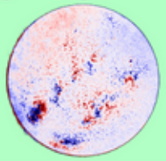
(a) SDO HMI 720s NRT Magnetograms





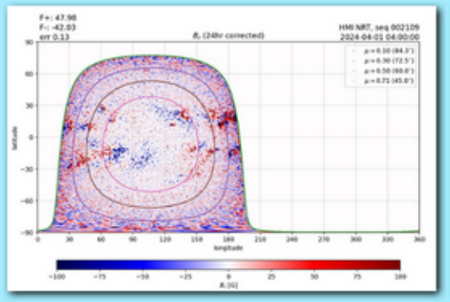
(b) SolO LL & Science Magnetograms



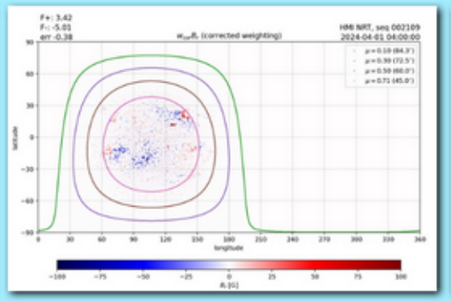


Full-Sun Magnetic Map Generation

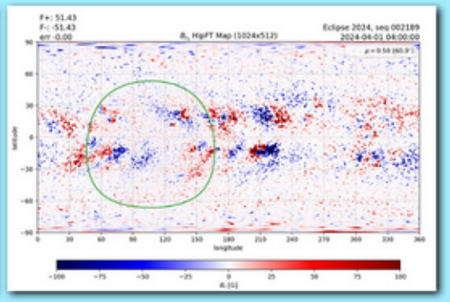
(c) Heliographic Mapping



(d) Assimilation Preparation



(e) Surface Flux Transport

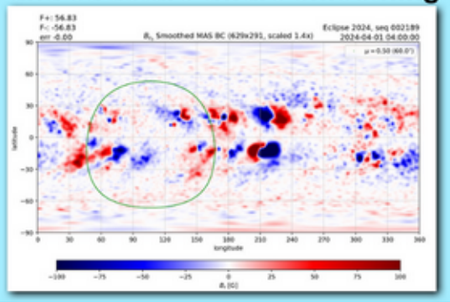


HipFT

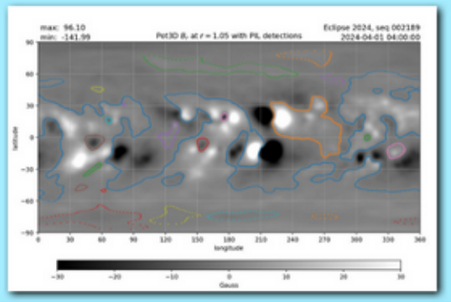
Multi-core CPU Workstation with Multiple GPUs

Model Boundary Conditions

(f) Flux-preserving re-mesh of maps and structure-aware smoothing



(g) Energization



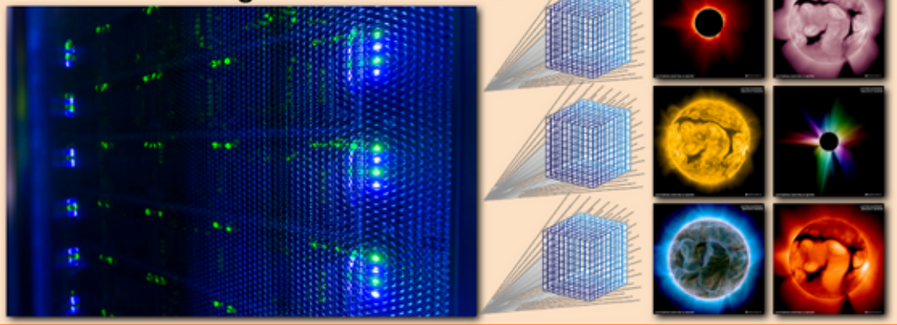
POT3D

Model Simulation

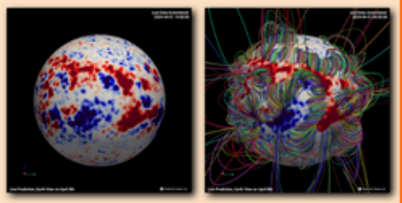
(h) Time-Evolving MHD Simulation

Post Processing Model Results

(i) Forward Modeling with Visualization



(j) Master renderer, work monitoring, additional visualizations



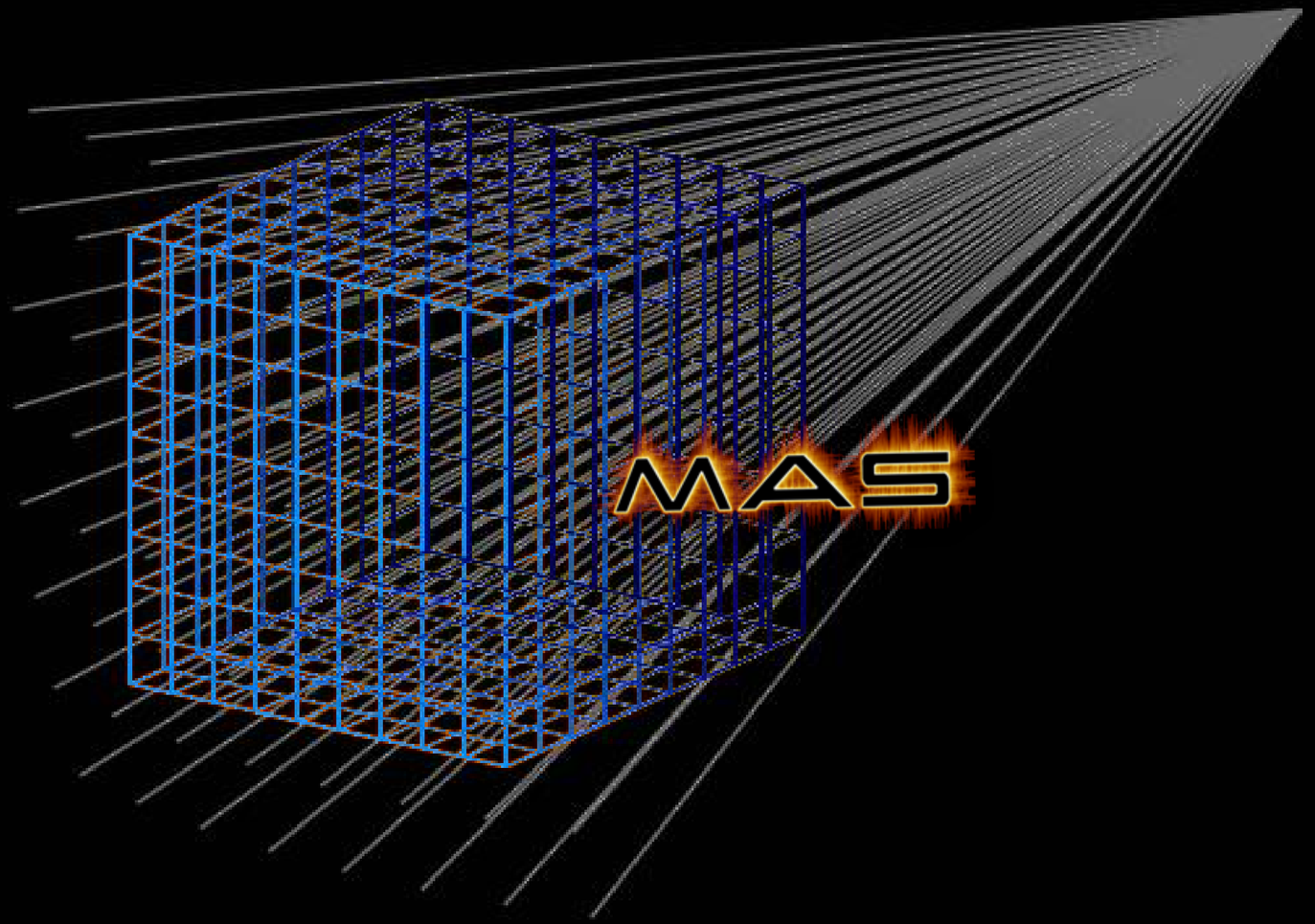
Release of Results

(k) PSI Live Prediction Web Site

predsci.com/eclipse2024

Generating White Light Images from the MHD Model

- Trace/integrate through the MHD data and compute brightness
- Tracing can be done from any location and field of view, allowing creation of synthetic observables of white light imagers



Some White Light Imagers

PARKER SOLAR PROBE

A MISSION TO TOUCH THE SUN

WISPR

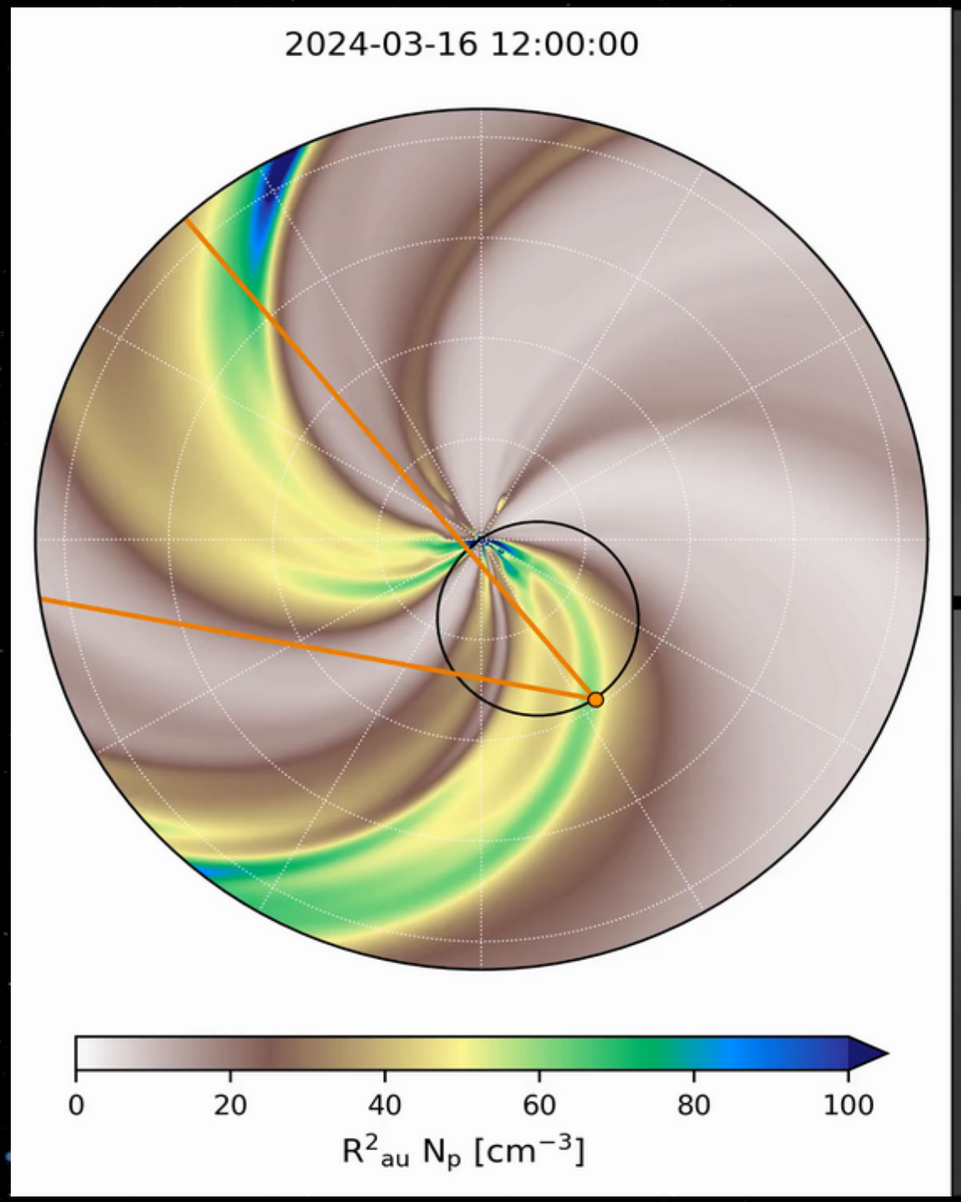
SoloHI

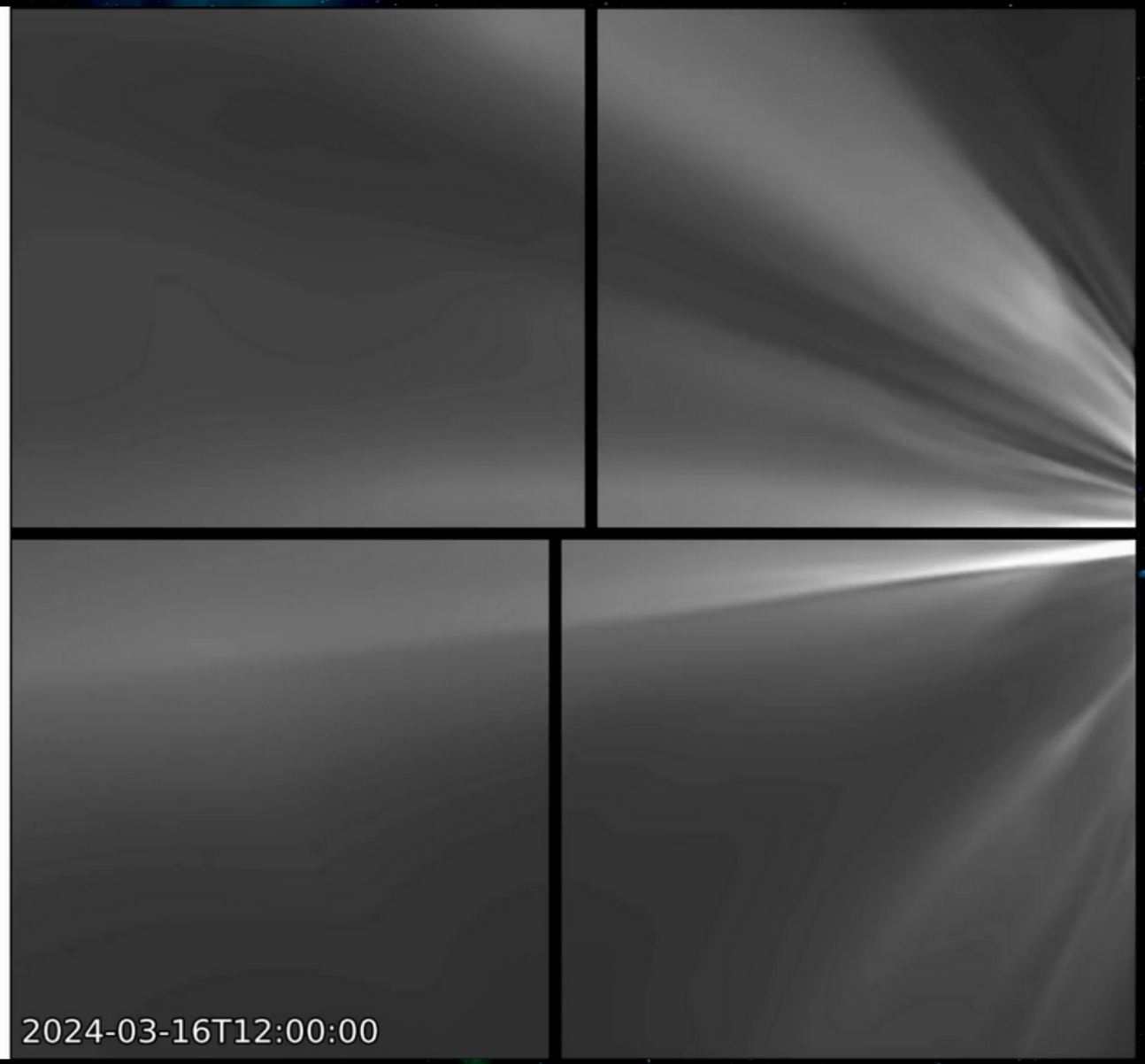
PUNCH

COMING SOON

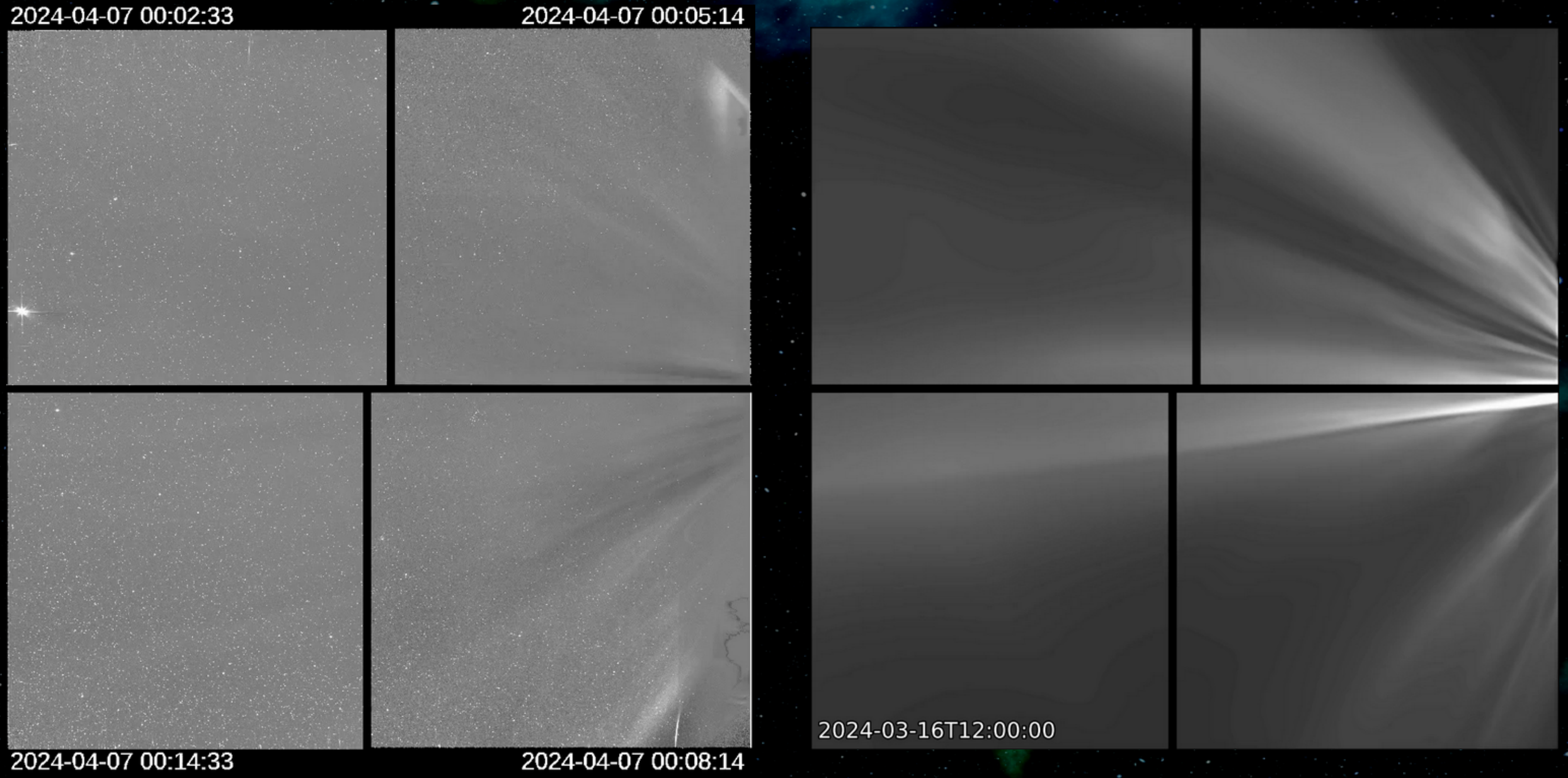
WFI

Solar Orbiter SoLoHI (Simulation)

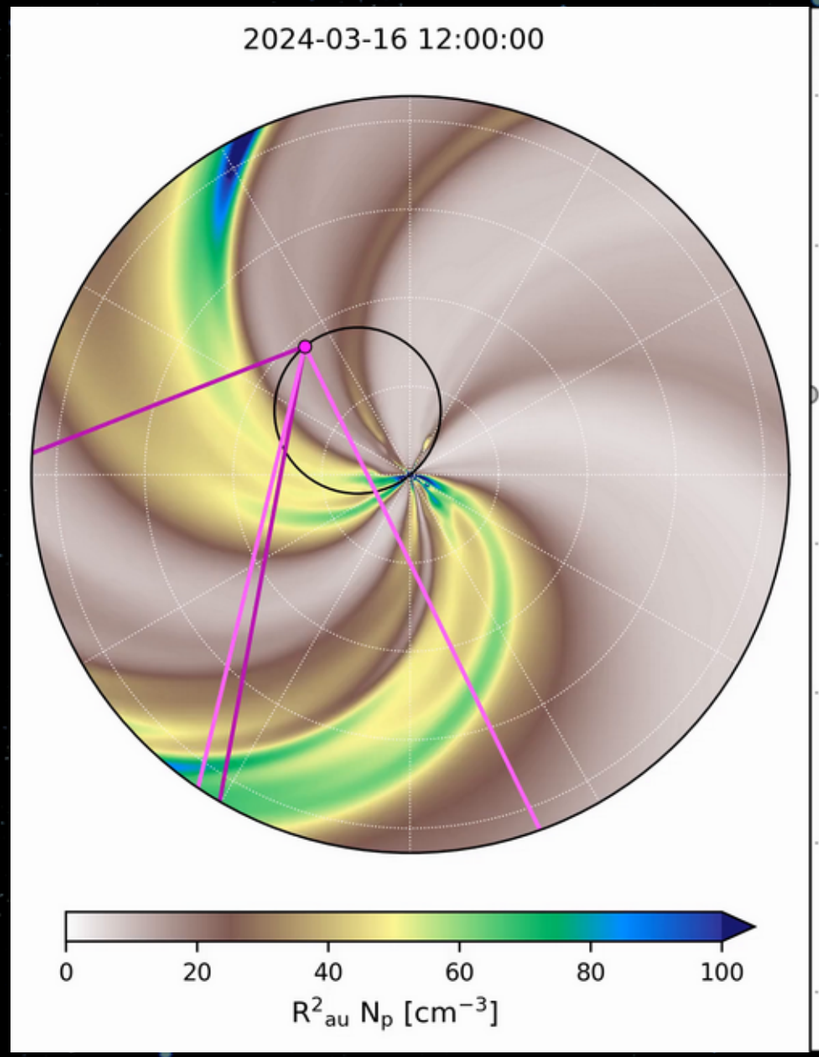


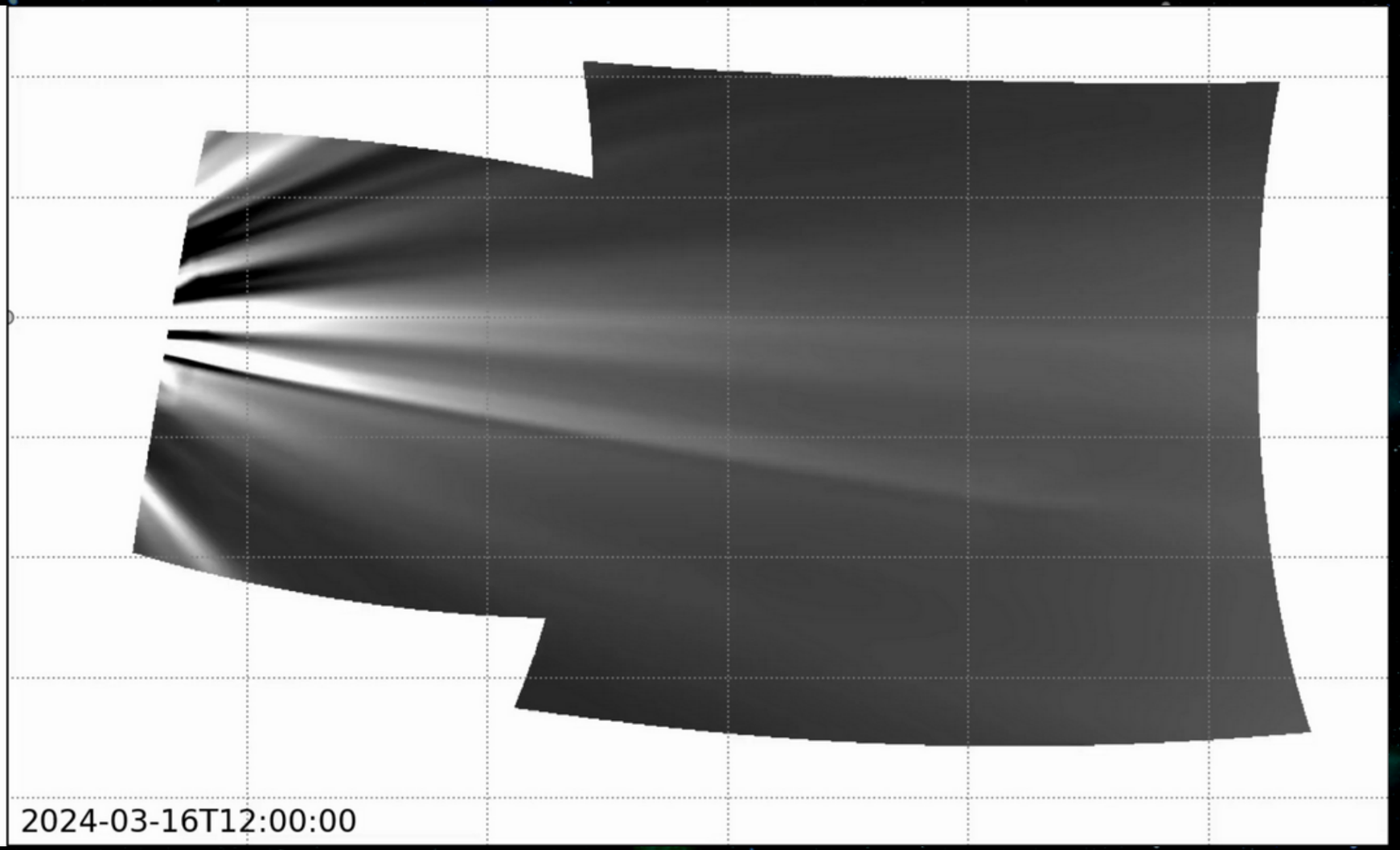


Solar Orbiter SoLoHI (Observation vs. Simulation)

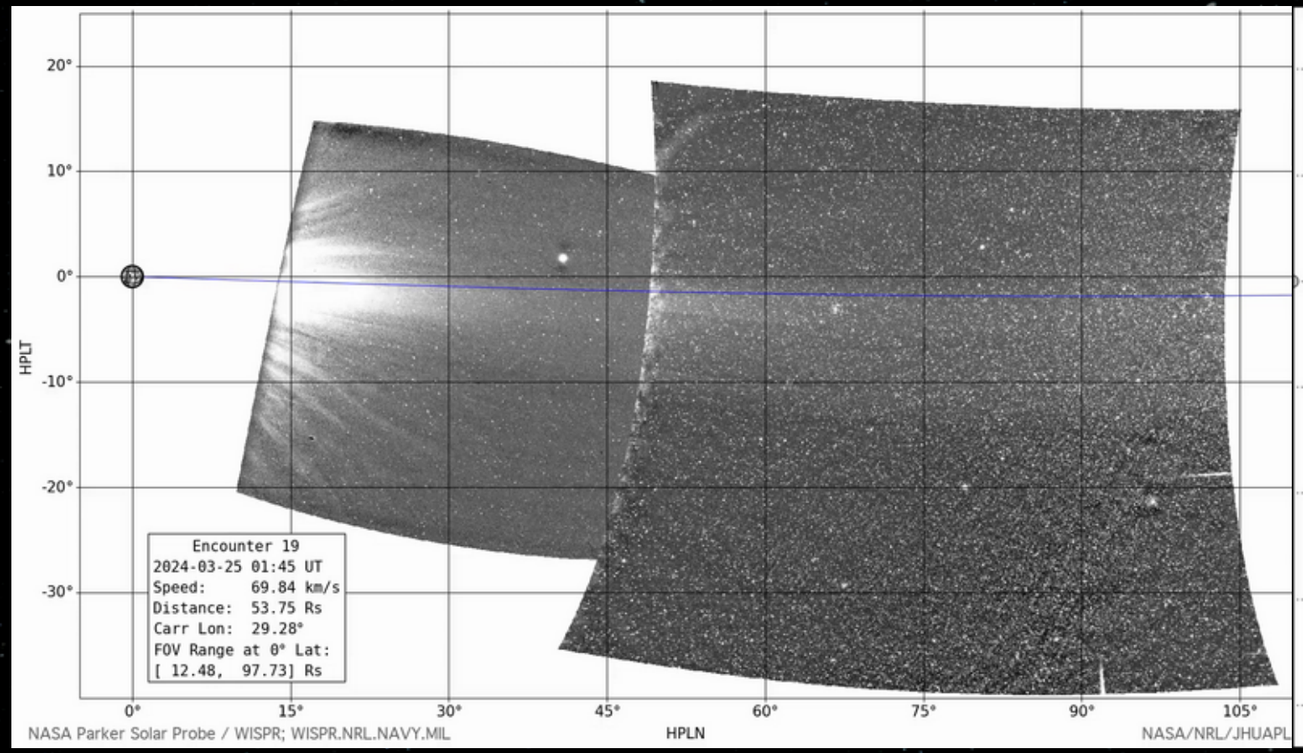


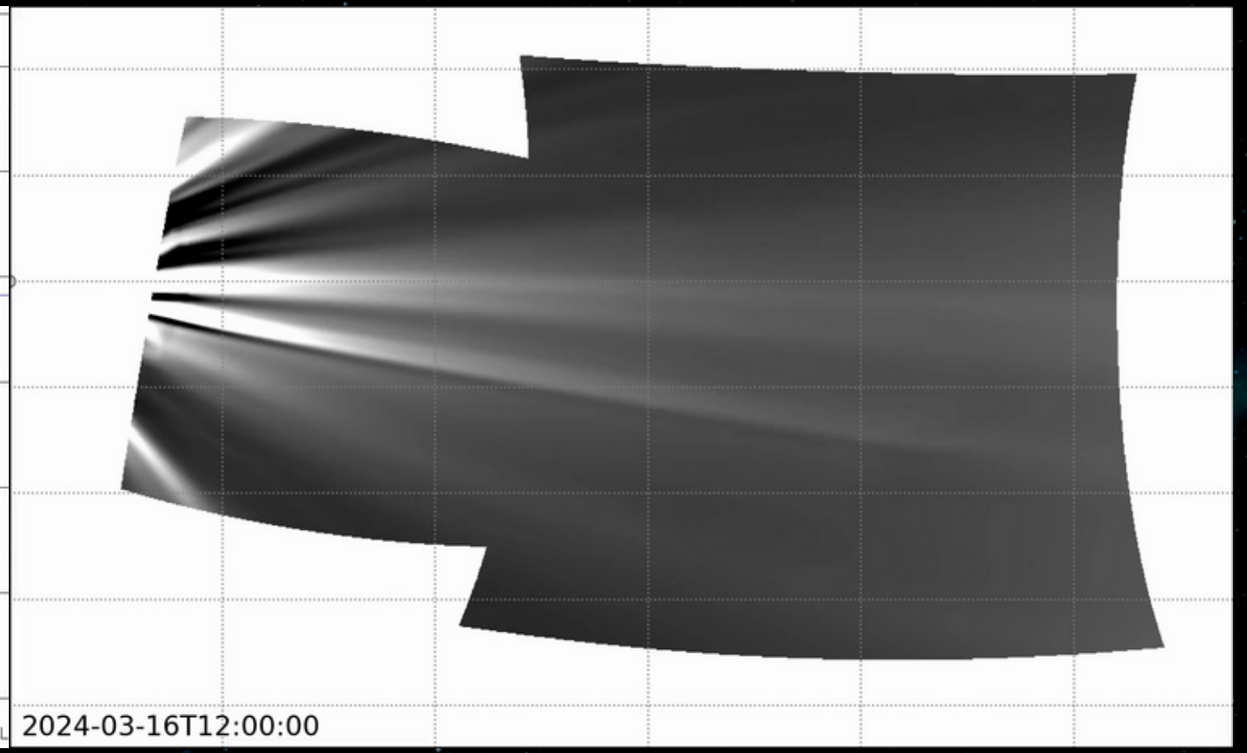
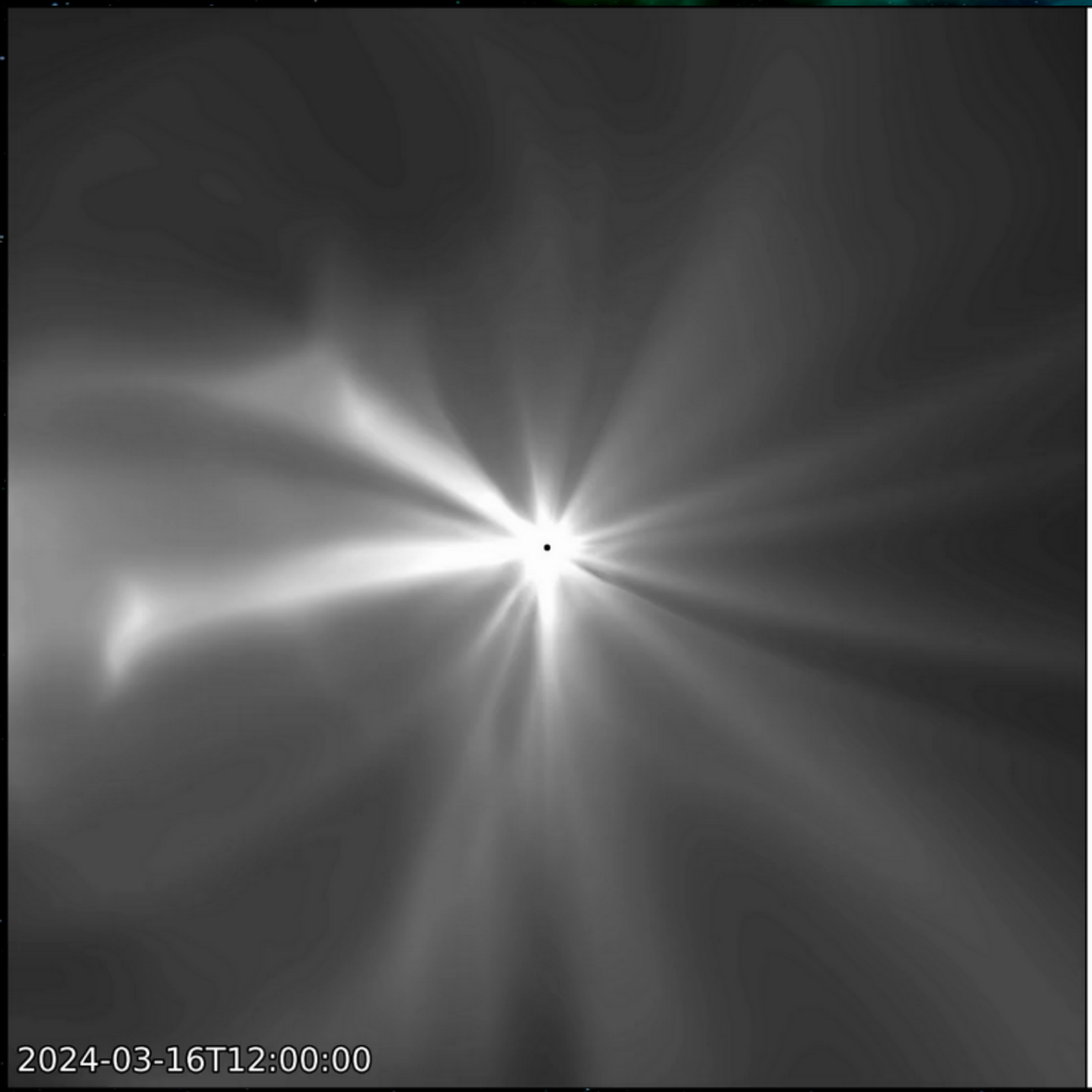
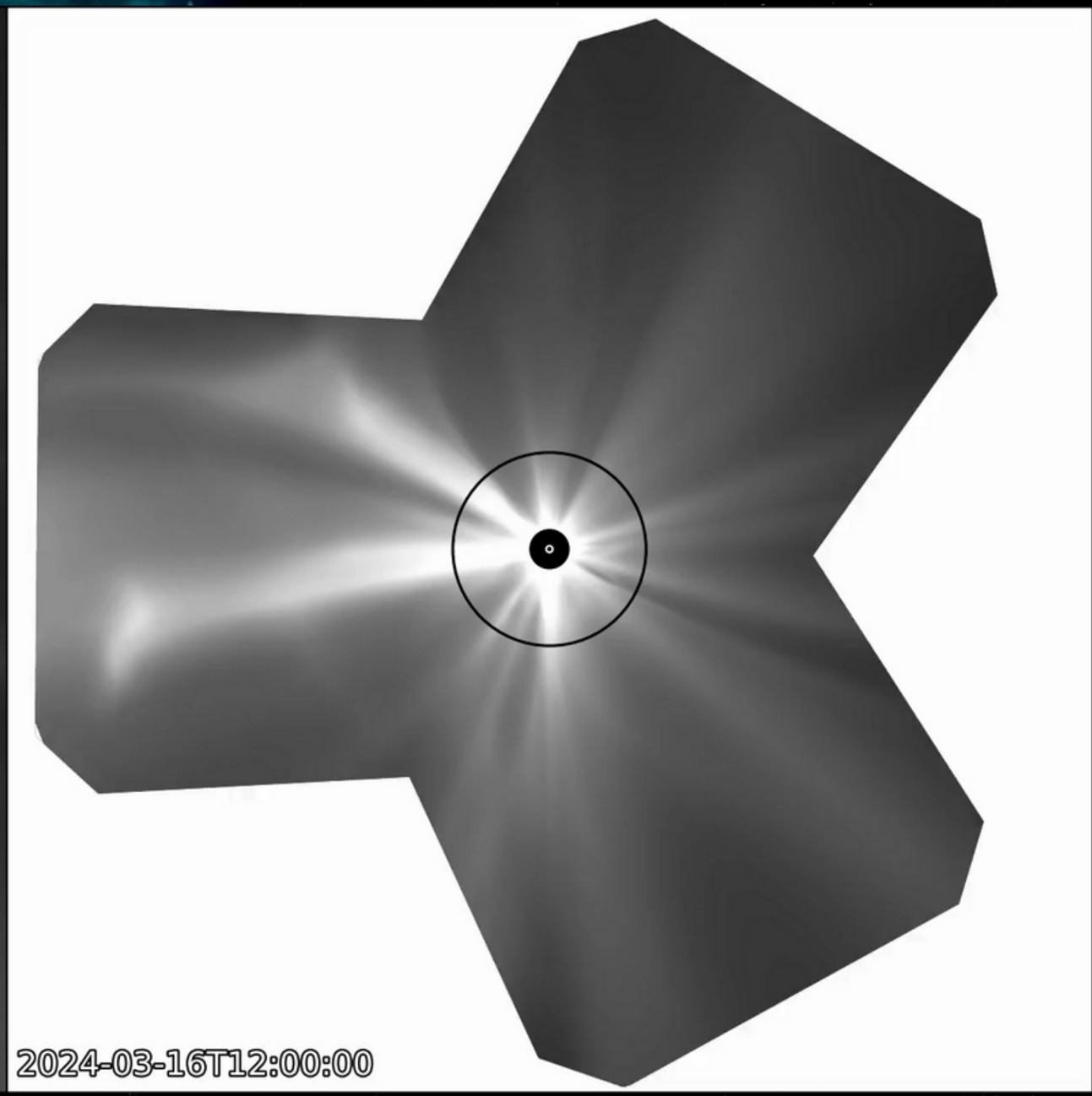
Parker Solar Probe WISPR (Simulation)





Parker Solar Probe WISPR (Observation vs. Simulation)





PUNCH Wide Field Imager (WFI) (Simulation)